Design of Strain Compensated InGaAs/GaAsSb Type-II Quantum Well Structures for Mid-infrared Photodiodes

Baile Chen, A. L. Holmes Jr, W.Y. Jiang, Jinrong Yuan.

Department of Electrical and Computer Engineering, University of Virginia,
Charlottesville, VA 22904-4743

***Abstract*—In this paper, the transition wavelength and wave function overlap of type-II $In_xGa_{1-x}As/GaAs_{1-y}Sb_y$ quantum wells are numerically calculated using a 4-band $k \cdot p$ Hamiltonian model. The simulation results indicate that absorption wavelength from 2µm to 4µm can be achieved with a symmetric strain compensated quantum well structure. For these structures, the transition wavelength and wave function overlap can be optimized by properly selecting the thicknesses and composition of the quantum well layers.**

I. Introduction and Background

Mid-wave infrared (MWIR) photodetectors are important for applications such as chemical sensing, gas monitoring, medical diagnostics, and free-space communications. Rubin Sidhu et. al. previously demonstrated a PIN photodetector on InP substrate using lattice matched InGaAs/GaAsSb type-II quantum wells (MQWs) as the absorption region. This device showed a peak detectivity of 3.8×10^9 $cm\cdot Hz^{0.5}W^{-1}$ at room temperature at 2.26 µm [1]. The cut-off wavelength for these detectors was 2.39 µm. In this paper, we investigate InGaAs/GaAsSb strain compensated quantum well absorption regions as a mean of achieving MWIR absorption. Our results show that absorption wavelengths well into the MWIR can be achieved.

In the InGaAs/GaAsSb type-II quantum well structure, electrons are confined in the conduction band of the InGaAs layer, while holes are confined in the valence band of GaAsSb layer. This band line-up will lead to a smaller effective bandgap and longer wavelength detection. Because the electrons and holes are separately confined in adjoining layers, the wave function overlap is significantly smaller than in bulk or type-I quantum well structures. A reduced wave function overlap reduces the responsivity of the photodiodes. Thus, optimal performance requires a wave function overlap as high as possible. The goal of this work is to look at the important factors in the design of InGaAs/GaAsSb quantum wells structures and how to optimize them for MWIR photodiode performance.

II. Simulation

The simulations were performed using APSYS from Crosslight Software Inc [2]. The 4 band $k \cdot p$ method is used for the calculation of the transition wavelength and wave function overlap between the ground state of electrons and heavy holes. The important material parameters (e.g. the band gaps, conduction band offsets, and elastic constants) used are consistent with recent theoretical and experimental results [3, 4]. In our initial work, we have simulated structure that are symmetric (i.e., the thickness and composition of each InGaAs and GaAsSb layer are the same) in order to understand the effects that material composition and layer thicknesses will have on the absorption wavelength and wavefunction overlap.

A. *Effects of Thickness on Transition Wavelength and Wave function Overlap*

Increases in the detection wavelength with thickness changes require a reduction in the wave function overlap. To further illustrate this point, Figure 1 plots the wave function overlap as a function of the detection wavelength. As can be seen in the figure, it is more effective to increase the thickness of InGaAs to get the longer transition wavelength, since it can achieve a larger increase of transition wavelength when sacrificing the same amount of wave function overlap.

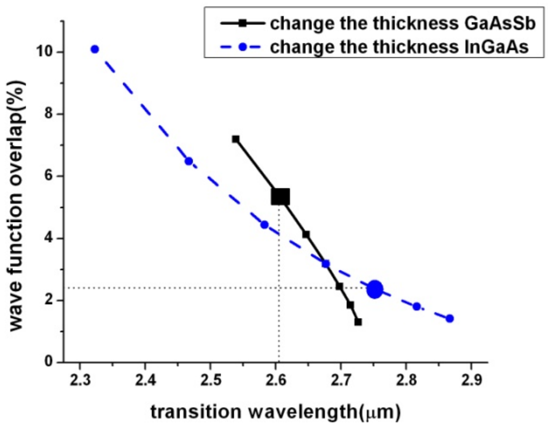
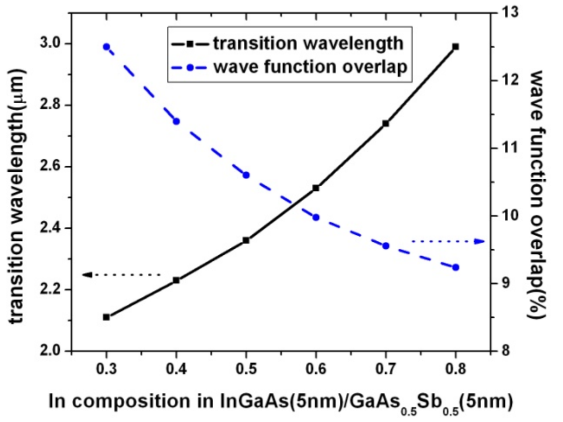


Figure 1 Wave function overlap vs. transition wavelength by changing the layer thickness of one material while keeping the layer thickness of the other material fixed at 7nm.

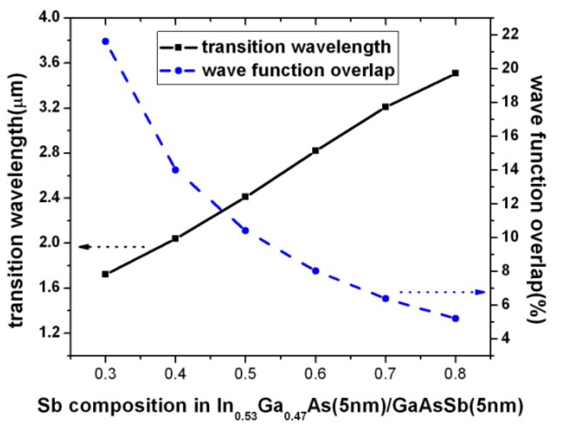
B. *Effects of Composition on the Transition Wavelength and Wave function Overlap*

For the longest detection wavelength, compressive strain should be added to both layers. While this approach would work for thin active regions used in semiconductor lasers, detectors require thick absorption regions for adequate performance. As a result, compressive strain can’t be used in the both materials.

The transition wavelength will increase as compressive strain is added to either InGaAs or GaAsSb as shown in Figure 2. The wave function overlap shows the opposite trend, since the wells become deeper. Also, the results show that it is more effective to add compressive strain in GaAsSb layer in order to achieve longer transition wavelength.



(a)



(b)

Figure 2.The dependence of the transition wavelength and the wave-function overlap vs. (a) the In composition change while keeping GaAsSb lattice-matched to InP and (b) the Sb composition change while keeping InGaAs lattice-matched to InP.

C. *Strain Compensated InGaAs/GaAsSb MQWs*

Since thick absorption regions are needed for high performance detectors, the InGaAs/GaAsSb MQW structure must have zero net strain. Under strain compensation condition, compressively strained GaAsSb layer and tensilely strained InGaAs will help to achieve longer transition wavelength.

To maximize the transition wavelength in strain compensated quantum well structures, several thickness and composition combinations were simulated. The transition wavelength as function of wave function overlap for different thicknesses and compositions are plotted in Figure 3. It can be concluded that the longest transition wavelength of 3.95μm can be achieved in this type-II quantum well structure. Using Figure 3, we can choose the design with wave function overlap as large as possible while keeping the same transition wavelength.

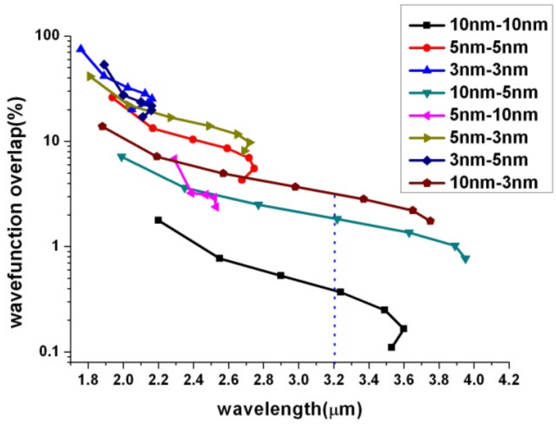


Figure 3.Under the strain compensation condition, wave function overlap vs. transition wavelegnth for different thickness combinations for both InGaAs and GaAsSb layers with Sb composition changing from 0.3 to 0.9.

III. CONCLUSIONS

In summary, 4-band $k \cdot p$ theory was used to calculated the transition wavelength and wave function overlap of InGaAs/GaAsSb type-II quantum wells structure. Also, the simulation indicates that the InGaAs/GaAsSb strain compensated type-II quantum wells have the potential for absorption across the 2-4μm spectral band. Last but not least, the procedure has been shown that thicker InGaAs layer, high Sb composition in GaAsSb layer are needed to optimize InGaAs/GaAsSb strain compensated quantum wells for use in the absorption region of InP-based mid-infrared photodiodes. Additional ways of further increasing the absorption wavelength of InGaAs/GaAsSb type-II quantum wells structures will be presented at the conference.

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